A FUZZY MULTI-CRITERIA ANALYSIS APPROACH FOR ASSESSING THE PERFORMANCE OF MODERN MANUFACTURING SYSTEMS

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Abstract: *Manufacturing systems have become more complex regarding the determination of critical overloads of cognitive tasks, due to the high technology. As a result, the nature of ergonomics has also changed into cognition. In this study, a quantitative model for determination of cognitive factors has been proposed to determine cognitive maps coupled with a fuzzy decision-making process to identify factors affecting modern manufacturing systems. An example is used throughout the study to explain the concepts.*

Keywords: *Fuzzy AHP, Cognitive Ergonomics, Modern Manufacturing Systems*

1. Introduction

Today, the technology is developing with rapid changes in manufacturing systems. The affect of this development raises the complexity in manufacturing including the production speed, variety of product, and shorter service times. These concepts bring about new manufacturing philosophies, which are Total Quality Management (TQM), Just-in-time (JIT), Computer Integrated Manufacturing (CIM), and Flexible Manufacturing Systems (FMS) (Zang,Vonderembse&Lim, 2003).

The cognitive complexity and the difficulty in decision making processes have become important factors by using the computers in modern manufacturing systems and with the studies of measuring complexity in tasks, cognitive ergonomics concepts are appeared at the beginning of the 1980s (Hollnagel, 2001).

The scientific interest, focused on how work affects the body, is consistent with the definition of classical ergonomics. This definition to the study of work that we now call classical ergonomics, remained valid for approximately 30 years, and is still the guideline for many practitioners. It was challenged by the concept of cognitive ergonomics, which means how work affects the mind, as well as how the mind affects work. The work-body dualism in classical ergonomics cannot simply be replaced by a work-mind dualism in cognitive ergonomics.

Cognitive ergonomics can be defined as the applied sciences of system design in a human-technology system. As it is observed today, mental work (thinking) is far more important than manual work (doing) (Hollnagel, 2001).

The common way to measure the cognitive complexity as indicated in the literature is using Petri nets are networks, which are graphical structures that reflect the behaviors of the operators to the system (Rauterberg, Schluep&Fjeld, 1997). But the structures of these networks are insufficient to express the cognition of manufacturing systems. Since mental workload is the amount of mental effort necessary to carry out a task and satisfactorily meet expectations, the focus of this study is the measure of weights of cognitive factors by a hierarchical way via cognitive maps (Tang,Koubek,Lighter&Salvendy, 1999). The cognitive maps are defined as graphical structures to describe the factors and the relationships of them. But, the literature on this kind of topics is insufficient and there are no similar studies on complex and computerized manufacturing systems.

One of the biggest molding factories is selected for this study and the cognitive maps are established that are specific to the FMS system. The hierarchical structure is analyzed using Analytical Hierarchy Process which is more suitable to investigate these kinds of structures and to express the abstract factors quantitatively. To prevent the subjectiveness of pairwise comparison of managers, fuzzy theory is used. These topics are explained in details in the next sections.

2. Identifying Cognitive Models and Modern Manufacturing Systems

It is pointed out that the notion of the mental model is very confusing to discuss how people reason about logical problems. It is a task which bears little resemblance to real decision making or aimed to understand how operators and general workers interact with highly complex manufacturing systems. In between lie mental models as a basis for interaction with relatively simple systems such as vehicular control, or to explain experiments on causal reasoning about simple mechanical devices. The confusion can be removed by seeing how workers are coupled to both their task (plant, machine) and the environment in which the task is carried out in manufacturing (Morray, 1998; Fjeld,Schluep&Rauterberg, 1998; Zang,Vonderembse&Lim, 2003).

Manufacturers face an increasingly uncertain external environment as the rate of the change in customer expectations, global competition and technology accelerates. In response, manufacturing flexibility becomes a critical dimension. Hence, in this study, Flexible Manufacturing Systems (FMS) are used as example of modern systems. A FMS combines NC and CNC machines, a material handling system (MHS), and a computer system to control the work. The components of the systems are: (1) NC and CNC machines (2) Robots and (3) Direct control unit for material handling system and CNC machines (DNC).

A framework of cognitive complexity *(CC)* of FMSs can be derived as $CC=FL+PS+CS-PV$ where FL represents system flexibility, PS represents production speed, CS represents customer satisfaction, and PV represents product variety. Observing the behavior of system in mind of managers is our basis for estimating cognitive factors. The cognitive structures of users are not direct observable, so a method and theory are needed to find parameters to estimate cognitive complexity (Rauterberg,Schluep&Fjeld, 1997; Rauterberg, 1992).

3. Basic Concepts

In this section, some topics are explained, including the Analytical Hierarchy Process and Fuzzy Theory, and their integration into the application.

3.1. Analytical Hierarchy Method (AHP)

In relative measurement of AHP, a preference judgment is expressed on each pair of elements. The pair of elements in a level of the hierarchy is compared with respect to the parent elements to which they relate in the level above.

Table 1. Fundamental scale of absolute numbers for pairwise comparisons

Low	1	Equal (low low)
	2	Between (medium low)
	3	Moderate (high low)
Medium	4	Between (low medium)
	5	Strong (medium medium)
	6	Between (high medium)
High	7	Very strong (low high)
	8	Between (medium high)
	9	Extreme (high high)

The fundamental scale of AHP, being an estimate of two ratio scale numbers, is involved in paired comparisons. The smaller element in a comparison is taken as the unit, and estimates how many times the dominant element is a multiple of that unit with respect to a common attribute, using a number from the fundamental scale. The fundamental scale of absolute numbers for pairwise comparisons is shown the Table 1 (Saaty, 1980).

3.2. Fuzzy Sets and Triangular Fuzzy Numbers

To facilitate the pairwise comparison process and avoid the complex and unreliable process of comparing fuzzy utilities, this paper represents triangular fuzzy numbers to solve multi-criteria analysis problems involving quantitative data. Triangular fuzzy numbers are used in the pairwise comparison process to express subjective assessments. The concept of fuzzy analysis is applied to solve the fuzzy reciprocal matrix for determining the criteria importance and alternative performance (Deng, 1999). The trapezoidal fuzzy numbers have high-coverage but there is no scale found to convert to these numbers in literature.

A triangular fuzzy number is a convex fuzzy set with a grade of membership between 0 and 1. This function satisfies the following conditions for the membership function $\mu_A(x)$:

(a) $\mu_A(x)= 0$, *for each x? (-8 ,*a_1*] U [*a_4*,+ 8)*
(b) $\mu_A(x)$ *is non-decreasing on* $[a_1,a_2]$ *and non-increasing on* $[a_3,a_4]$
(c) $\mu_A(x)=1$, *for each x?* $[a_2,a_3]$

4. Expression of Quantitatively of Performance Factors

In the first step, the Analytic Hierarchy Process must examine the vertical relationships on the cognitive maps. The factors' weights through the vertical subfactors are investigated using a pairwise comparison matrix as explained above.

The comparisons carry the subjectiveness of researchers or managers. To avoid this problem, and to reflect the other views into evaluation these pairwise comparison matrixes convert to the fuzzy numbers using the rule in Table 2. Because of the complexity in operations triangular fuzzy numbers are used here. Beside this, the inconsistency level of matrices must be in the acceptable level of 10%.

The arithmetic of triangular fuzzy numbers used for the calculation of the fuzzy matrices. Every real number has three parameters in fuzzy operations. After these studies the weights must be found from the judgment matrixes to use the factor ratings quantitatively as shown below:

$$Wj = \frac{\sum_{j=1}^{k} \bar{a}ij}{\sum_{i=1}^{k}\sum_{j=1}^{k} \bar{a}ij} \qquad (1)$$

where $W = (W_1,W_2,W_{3\,,\ldots,}W_m)$ and $\bar{a}_{ij}$'s are fuzzy numbers.

The decision matrix (X) determined from subfactors using the same way as (W):

$$X = \begin{bmatrix} x_{11} & x_{12} & \ldots\ldots & x_{1m} \\ x_{21} & x_{22} & \ldots\ldots & x_{2m} \\ \ldots. & \ldots. & \ldots\ldots & \ldots\ldots. \\ x_{n1} & x_{n2} & \ldots\ldots & x_{nm} \end{bmatrix} \qquad (2)$$

where $i=1,2,\ldots,n$; $j=1,2,\ldots,m$ and $k=m$ or n depending on the performance ratings of alternatives or weights of criteria involved.

A fuzzy performance matrix *(Z)* representing the overall of all alternatives with respect to each criterion can therefore be obtained by multiplying the vector by the decision matrix. The arithmetic operations on these fuzzy numbers are based on the fuzzy arithmetic for all levels.

$$
Z = \begin{bmatrix} w_1 x_{11} & w_2 x_{12} & \ldots\ldots & w_m x_{1m} \\ w_1 x_{21} & w_2 x_{22} & \ldots\ldots & w_m x_{2m} \\ \ldots. & \ldots. & \ldots\ldots & \ldots\ldots. \\ w_1 x_{n1} & w_2 x_{n2} & \ldots\ldots & w_m x_{nm} \end{bmatrix} \tag{3}
$$

The same operations used for every level of performance via cognitive map's hierarchical structure and the weights determined. Tables of relationships of all levels and the global affects are established (Deng, 1999).

5. Application

In this section of the study, an attempt to develop a model has been made for measurement system, using a cognitive map and analytical hierarchy process using fuzzy theory to identify affecting factors and to express them quantitatively as explained above. An example of Flexible Manufacturing Systems is used throughout this section to explain the study.

5.1. Determination of Cognitive Factors

Determination of cognitive factors is a quite complex procedure. The brainstorm with the companies' managers, the fact of production, and the observations in the company are defined as the factors and subfactors. The 27 factors and subfactors are determined which the first level of the hierarchy is explained above and the subfactors are dispersed according to the first level.

5.2. Establishing of Cognitive Maps and Structure of Hierarchy

The molding sector and the biggest molding company of Turkey are selected for this study. After an interview with the companies' necessities with the managers, we tried to establish a 5-level hierarchical structure. This map is representing a general structure for companies and put into practice for the other companies and for the other sectors with some small changes.

The cognitive map of FMS system factors is quite complex and these systems encounter a lot of horizontal affects in every level and for most subcomponents of map. In first level, customer satisfaction is affected from production speed and product variety of 10% and 15%, respectively in our cognitive map.

In the second level, routing flexibility affects material-handling flexibility for 10% increasingly and quality affects total cost 15% decreasingly. The material handling flexibility has two relations vertically to level above and the routing flexibility have three relations. This kind of relations makes the system's hierarchical structure very complex. DNC factor is the very important subfactor of flow speed and have two relations above and 8% affects horizontally for CNC. The volume factor in level 4 makes the relationships very hard to solve.

As known the FMS system has various flexibility factors. Some of these flexibilities have direct affect to system that they located on the above level in the hierarchical structures according to the company's necessities.

5.3. Expression of Quantitatively of FMS Factors

The pairwise comparison matrix of first level *(C_{sys})* is shown below as an example for the first level. The fuzzy equivalence matrix calculated according to Table 2.

$$
Csys = \begin{bmatrix} 1 & 3 & 5 & 4 \\ 1/3 & 1 & 3 & 3 \\ 1/5 & 1/3 & 1 & 3 \\ 1/4 & 1/3 & 1/3 & 1 \end{bmatrix}
$$

Using the formula (1), the weight vector *(W)* for the decision problem determined using fuzzy arithmetic

where $W = (W_1, W_2, W_3, W_4)$.

A fuzzy performance matrix *(Z)* representing the overall of all alternatives with respect to each criterion can therefore be obtained by multiplying vector by the decision matrix with formulas (2) and (3). The same operations used for every level via cognitive map's hierarchical structure and the weights determined.

Table 2. Fuzzy number used for making qualitative assessments

Fuzzy Numbers	Membership Function
$\bar{1}$	(1,1,3) for x=1
$\bar{9}$	(7,9,11) for x=9
$\bar{x}$	(x-2,x,x+2) otherwise.

5.4. Determination of Real Numbers

Researchers use several methods of conversion. The well known and a commonly used method is calculating the mean of fuzzy numbers. However, the shape of our fuzzy numbers led us to use the median method.

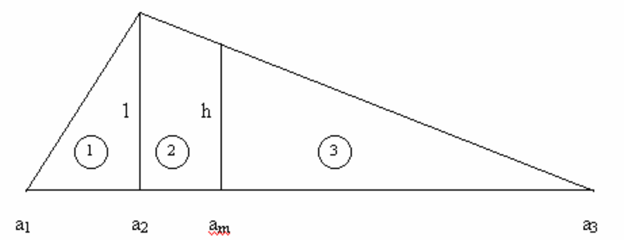

Figure 1. The shape of triangular fuzzy numbers

Therefore, the mean of the numbers (a_2) does not reflect real the structure. Thus, the median of the fuzzy numbers (a_m) must be found to express the real situation. We have to calculate triangle similarities to find the (a_m) shown in Fig 1.

5.5. Pareto Analysis

The pareto analysis is used to determine the factors both important and less important. According to the coverage of common 20/80 rules that is the factors of 80% is important and the remaining is less important. There are found 15 important factors that they are affected the system cognitively.

6. Discussions and Conclusion

In this paper, a cognitive approach for identifying the factors and subfactors effecting system has been developed and explained by cognitive maps and evaluated with fuzzy pairwise comparison, in the first time. The benefits of this approach show three new improvements:

- The complex structure of cognition is established for the FMS system by cognitive mapping technique, firstly.
- The more suited fuzzy theory has been applied to reflect the dynamic structure of the system and to prevent the subjectiveness of the decisions of managers in pairwise comparison matrices.
- The dynamic nature of the internal and external environments has been included to the performance measurement system.

Using these three improvements, this study will be the basis of the cognitive performance measurement of modern manufacturing systems. The important factors which have been identified by the results of the Pareto analysis could be monitored frequently and the less important factors could be monitored occasionally in certain periods. Additionally, this study could serve as a decision support system to the managers to solve the problems that arise in the performance measurement system. To the best of the authors' knowledge, this is the first study on complex and computerized manufacturing systems.

The AHP technique is based on the independence of the factors and subfactors at every level. To obtain more efficient results, the recently developed Analytical Network Process (ANP) can be considered bearing in mind the dependency of the factors. Besides, special software can be utilized to monitor the system and the changes of hierarchy better in different manufacturing systems.

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